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TUNNEL LOCATION BY GAS FLOW

P. L. Lagus, T. H. Pierce and D. R. Grine

Systems, Science and Software
P. O. Box 1620
La Jolla, CA 92038

January 15, 1979

Final Report for Period March 13, 1978 - January 15, 1979

CONTRACT NO. DNA001-78-C-0022

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Prepared for

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Field experiments determined the rates of gas flow from boreholes, through a fractured igneous rock, to a tunnel. Equivalent crack widths were calculated at 0.005 inch or larger. Laboratory experiments showed that acetylene-oxygen mixtures would detonate in a 0.005-inch crack. It appears feasible to locate tunnels by injecting an explosive gas or liquid mixture into a nearby borehole and initiating an explosion in the tunnel from a borehole. (over)

20. A passive seismic network would be used to locate the explosion source.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (continued)

LIST OF TABLES

1. INTRODUCTION AND SUMMARY

Defense Advanced Research Agency (DARPA) has funded a program to improve capabilities to detect existing, hidden tunnels. Systems, Science and Software, (S^3), under Contract Number N00123-76-C-1779, investigated both the seismic and gas flow characteristics of the rocks surrounding a test mine. Gas injection measurements showed communication by both pressure rise and arrival of tracer gas between the two boreholes from the surface on one side of the mine. Tracer gas arrivals were also measured in the mine and escaping air could be heard during pressurization.

The initial results made cross-borehole measurements of gas flow or liquid flow seem a promising method for detection of hidden tunnels. If a tunnel is between an injection point and a measurement hole, the high pressure flow would go preferentially into the tunnel rather than communicating to the other borehole. Measurements along a line of boreholes spaced much more modely than a tunnel diameter should be useful as a validation testing for tunnel detection. p.1473

To make the detection more certain, S^3 proposed that the gas or liquid flow be composed of an explosive mixture. After allowing sufficient time for this mixture to enter the tunnel, detonation would be initiated from one of the boreholes in the mixture filling the cracks in the surrounding rock. If this detonation were to successfully propagate through the cracks and into the tunnels, it could initiate the explosive mixture in the tunnel. The resulting explosion could then allow the tunnel location to be determined by passive seismic ranging on the surface.

For the technique to succeed, it is necessary that we be able to inject an explosive mixture from a borehole through

cracks into the tunnel; that the detonation of the explosive mixture be able to propagate through the cracks and enter the tunnels; and that detonation in the cracks must initiate detonation in the explosive within the tunnel.

We report here on an experimental effort performed by S^3 for DARPA under Contract Number DNA001-78-C-0072 during 1978, to test feasibility of both the flow measurements on passive substances and on the use of explosive injection techniques for tunnel location. The work included field measurements on gas and liquid flow at the Hazel A Mine near Gold Hill, Colorado, and an experimental program on detonation of gas mixtures in thin cracks, performed at S^3's Green Farm Test Site.

The field investigation at Gold Hill was designed to document the relative ease of injecting inert gases and liquids from surface boreholes into a tunnel through pre-existing fracture patterns.

We intended to perform complete explosive injection and detonation experiments, but could not obtain a limitation of liability agreement from the mine owner.

The Green Farm experimental effort was directed toward identifying likely gaseous explosive mixtures and determining minimum crack thicknesses through which an explosion (detonation) in these gases would propagate.

In Section 2, the major conclusions of this undertaking are presented. In Section 3, we provide a background of the tunnel detection problem and the previous year's investigation. Section 4 documents the gas and liquid flow field experiments. Section 5 describes in detail the experimental gas detonation experiments in cracks performed at the Green Farm Test Site, and Section 6 presents recommendations for future work.

2. CONCLUSIONS

On the basis of the experimental and field studies undertaken during the course of this work, several conclusions germane to the tunnel detection problem can be drawn.

1. The technique of utilizing a wide-spaced straddle packer in conjunction with compressed air allows one to rapidly locate zones of high permeability and/or reasonably open cracks within a borehole.

2. Injection of distinct tracer gases in the zone of maximum flow within each borehole provided relatively rapid communication with the tunnel complex. In one case, the tunnel was almost 18 meters from the borehole. In the second, the tunnel was ten meters from the borehole.

3. The liquid tracers, as might be expected, take a considerably longer time to flow to the region of the tunnel complex. The liquid tracers did not follow the same flow paths as the gas tracers did. In fact, the liquid tracers would not have intersected the tunnel proper. They were discovered only in ten meter deep boreholes drilled into the tunnel floor.

4. Gas explosions, specifically of acetylene and oxygen, can propagate in extremely thin cracks over substantial distances. Experiments performed at our Green Farm Test Site show that acetylene/oxygen mixtures at atmospheric pressure can detonate through cracks five-thousandths (0.005) of an inch thick.

5. Utilizing the rapid straddle pack technique for locating zones of maximum flow in boreholes in conjunction with injection of acetylene-air or acetylene-oxygen mixtures over appropriate lengths of time could prove to be a very useful device in producing line detonations within tunnels. The detonations could be used as a source for seismic detection identification of suspected tunnels.

3. BACKGROUND

Injection of a fluid into a section of a borehole will transmit pressure to fluids in the surrounding rock. The transmitted pressure pulse will move away from the borehole at a rate depending on the characteristics of the rock and of the fluid filling its pore spaces. The injected fluid will flow into the rock, driving the original fluid ahead of it, and moving out at a velocity usually much slower than that of the transmitted pressure pulse. The velocities and shapes of the transmitted pressure pulse and even more of concentrations of the injected fluid can be used to determine average porosities and permeabilities of rock between the injection borehole and a borehole used for measurements. An extensive literature exists on flow of liquids in such circumstances because of the importance of the phenomenology in secondary production of oil. Gas flow techniques are less developed but have been used recently in studies of possible leak paths from underground nuclear explosions, fracturing of rock for <u>in situ</u> oil shale retorting, and our previous tunnel location work.

A tunnel, that is not sealed against flow from the surrounding rocks, should act as a sink for high-pressure gas or liquid flow because it is at atmospheric pressure. We do not expect hidden tunnels of military interest to have impermeable liners because such liners are both expensive and slow to install. We therefore would expect the presence of a tunnel between two boreholes to interrupt both the transmitted pressure pulse and the flow of gas or liquid tracers. However, such an interruption could also occur between two boreholes because an impermeable zones lies between them. Injection and detonation of an explosive mixture in the tunnel would distinguish the tunnel from an impermeable zone. The

localized detonation in the tunnel could be detected and located by an array of seismic receivers on the surface.

In previous work on the DARPA tunnel location program, S^3 investigated the effects of a tunnel on the flow of gas between the surface boreholes. Figure 1 is a scaled drawing of surface boreholes near the Hazel A mine with a cross-section of the adit. The mine is at the Gold Hill Test Site (Sec. 12, T1N, R72W, Boulder County, Colorado) which has been used by several other DARPA contractors for tunnel location studies. The mine adit is driven entirely in Boulder Creek granodiorite, a very impermeable igneous rock with negligible porosity. Joints in the rock are the only significant carriers of ground water or paths for gas flow. Total porosity in the rock mass, probably mostly in the joints, is estimated at less than one percent. The granodiorite is locally altered along a group of NE-trending quartz veins that constitute the mineralized zones formerly mined. These altered zones are up to one meter wide. The four largest veins crossing the mine adit are marked by cross-drifts.

The ten meter drop in water level between October 1976 and December 1976, shown in Figure 1, resulted from gravity draining of water through the joint system into the mine adit. During this interval, boreholes were drilled out from the adit, as shown in Figure 1, and intersected permeable joints to permit the water drainage.

In Hole B, about ten meters from the adit as shown in Figure 1, a five meter zone above the water level was packed off and pressurized with $\sim$18 psig compressed air marked with Freon 13B1 tracer gas. Holes A, D, and E were packed off at four meters from the surface and monitored for pressure changes and arrival of tracer gas. Grab samples were taken in the mine to determine tracer gas arrival. A pressure arrival was noted at Hole A at ten minutes after

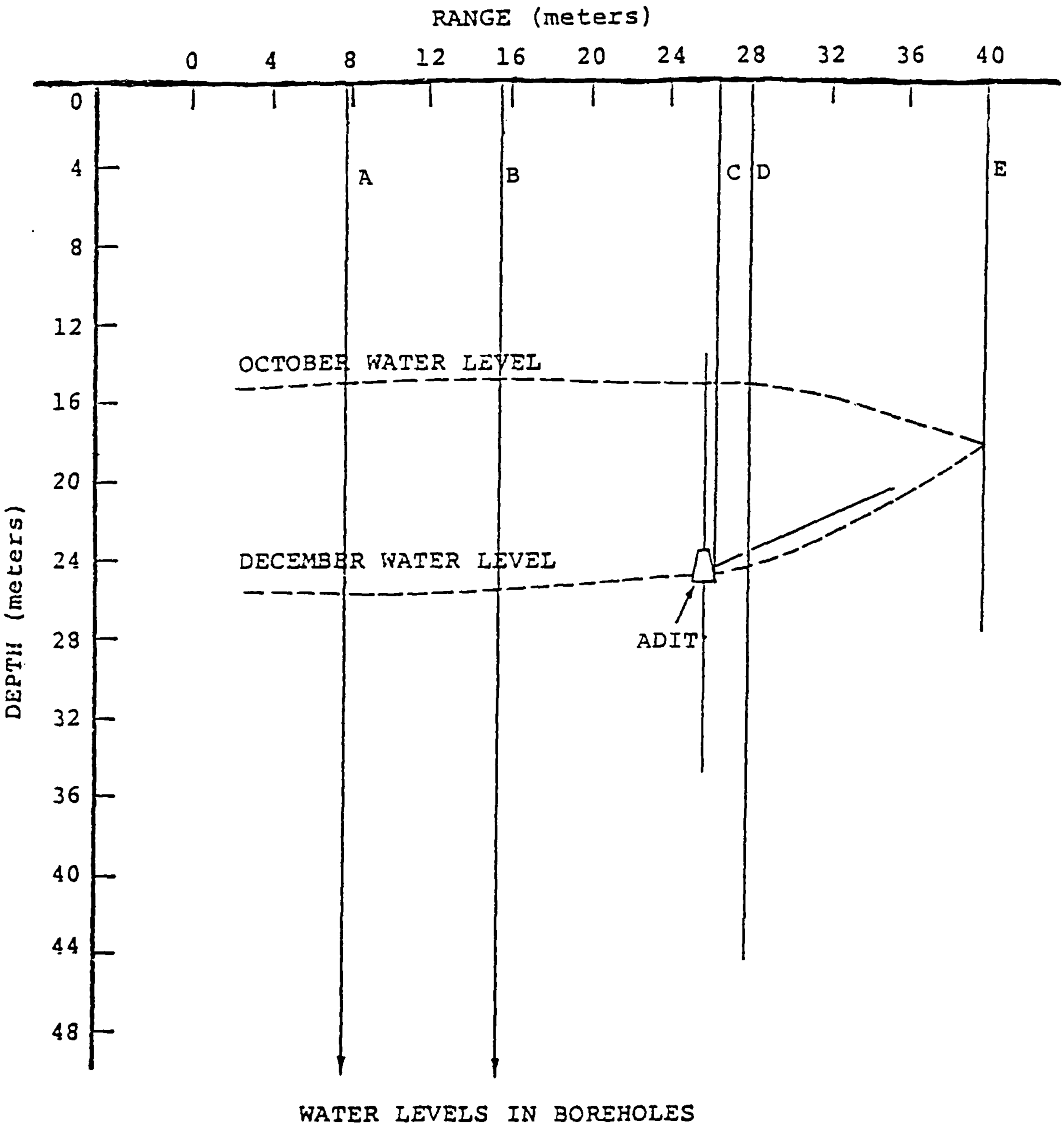


Figure 1. Hazel A mine boreholes

pressurization and tracer gas arrival at about 45 minutes. Tracer gas was detected in the mine at about 75 minutes. No pressure or tracer gas arrivals were noted at Holes D or E. The procedure was repeated for the zone from five meters to ten meters above the water table in Hole B using sulfur hexafluoride (SF_6) tracer gas. Pressure arrival at Hole A was at eight minutes and tracer gas arrival at about 30 minutes. Tracer gas arrival at the tunnel was about 30 minutes after injection began. No arrivals of pressure or tracer gas were detected at Holes D or E. During both experiments an audible hiss of pressurized air was heard in the adit and small fountains of water were ejected from the vertical downward holes in the adit.

The experiments showed that gas injected into a surface borehole in the low porosity jointed rock traveled into a mine adit approximately ten meters distant. The flow rate of air into the hole was 83 SCF/hour in the zero to five meter zone above the table and 12 SCF/hour in the five to ten meter zone above the water table. Both zones were pressurized to ~18 psig. The water fountains from the drill holes in the adit also showed that even small pressurizations would push liquid along the joint zones into the adit.

During a visit to the NOTS, China Lake Test Site at the Tungsten Peak mine, we observed that joint communication with the mine from a surface borehole about 20 feet distant was so effective that the borehole could not be filled with water from a water truck. A large quantity of water pumped into the borehole immediately ran into the adit and dumped on the miners who were working there.

Both our experiments at Gold Hill and Lawrence Livermore Laboratory (LLL) experience at Tungsten Peak show that a gaseous or liquid explosive could be injected into a surface borehole to emerge in a nearby adit. It is

obvious that very different flow characteristics result from the differences in openness of joints or filling of joints with alteration minerals.

Liquid explosives have been used by several organizations to increase rock permeability and thus increase flow of oil or natural gas into boreholes. One method requires pressurization of the explosive into a borehole so that the explosive is displaced into cracks in the surrounding rock and can be detonated in the cracks. The explosives successfully detonated in the cracks in the rocks have included EL-389-B, a DuPont desensitized nitroglycerin-base mixture, (Reference 1), TAL-1005C, a proprietary mixture made by Talley-Frac Corporation (Reference 2), and Astrolite, a double-base explosive produced by Petroleum Technology Corporation (References 3 and 4). To our knowledge, none of these explosives has been injected through cracks into an underground opening and detonated from a borehole into the opening. If the explosive is coming up from the floor of an adit, a puddle in the adit should detonate but if the explosive is falling in a stream of drops, the explosive train would be broken and the explosive in an adit would not detonate.

Because there may be problems in injecting liquid explosives into voids from surface boreholes and detonating them from the boreholes, we experimented with both gases and liquids in the new flow experiments at Gold Hill. Our first experiments were to repeat the gas flow measurements described above and extend them to pressurizations of all of the available surface boreholes except that one (C) that actually intersects the adit. By quantitative measurements of tracer gas at several points in the adit, we determined the concentrations of injected gas in the adit and whether explosive gas injections would be likely to produce explosions in the adit.

We did liquid injections using dyed inert liquid to mark injection points into the mine and get at least rough determinations of the amount of liquid that would flow into the mine for various injection rates into the various holes. We also observed the mode of entry into the mine to evaluate whether a detonation of the explosive through the cracks would be likely to detonate the explosive injected into the mine.

We tested candidate explosive gases at our Green Farm Test Site to determine how thin a crack would propagate an explosion in the gases. All the liquid explosives that have been successfully detonated in joints will propagate detonations in cracks open less than one millimeter. On another project we had demonstrated a propagating detonation of Talley-Frac explosive in a crack open 0.004 inch.

4. GAS AND LIQUID FLOW EXPERIMENTS AT GOLD HILL

A cross-sectional view of the location boreholes and the tunnel was provided in Figure 1. The total depths are over 50 meters for holes A and B, and as shown for holes D and E. Hole C penetrated the tunnel on the north wall. During the course of all gas flow measurements, Hole C was packed off one meter from its entrance to the tunnel and also 3.5 meters from the surface.

The surface spacing of the boreholes is presented in Figure 2. Note that the labels for these boreholes differ from those used in last year's report. In addition, a series of 10-meter boreholes was drilled outward from the tunnel walls during the previous year's testing. These were shown in Figure 1 and are shown in perspective in Figure 3. The boreholes vertically up and 30 degrees above horizontal were free of water. The boreholes vertically down were completely filled with water. During the course of all gas flow experiments the vertical up and horizontal holes were packed off one meter from the collar. Pressures were continuously monitored in the vertical up, and horizontal boreholes and in Borehole C using Validyne Model DP-15 pressure transducers with a sensitivity of one psi full-scale and a precision of one percent. No pressure arrivals were noted in any of these holes during the course of the gas flow experiments.

Reconnaissance-type testing was initiated utilizing compressed air provided by a spray paint compressor. Each hole was individually packed off at 3.5 meters below the ground surface and pressurized with compressed air. A single inflatable packer (see Figure 4) was used for these tests. Driving pressure, compressed air flow rate, and downhole pressures were monitored using a manifold as shown in Figure 5.

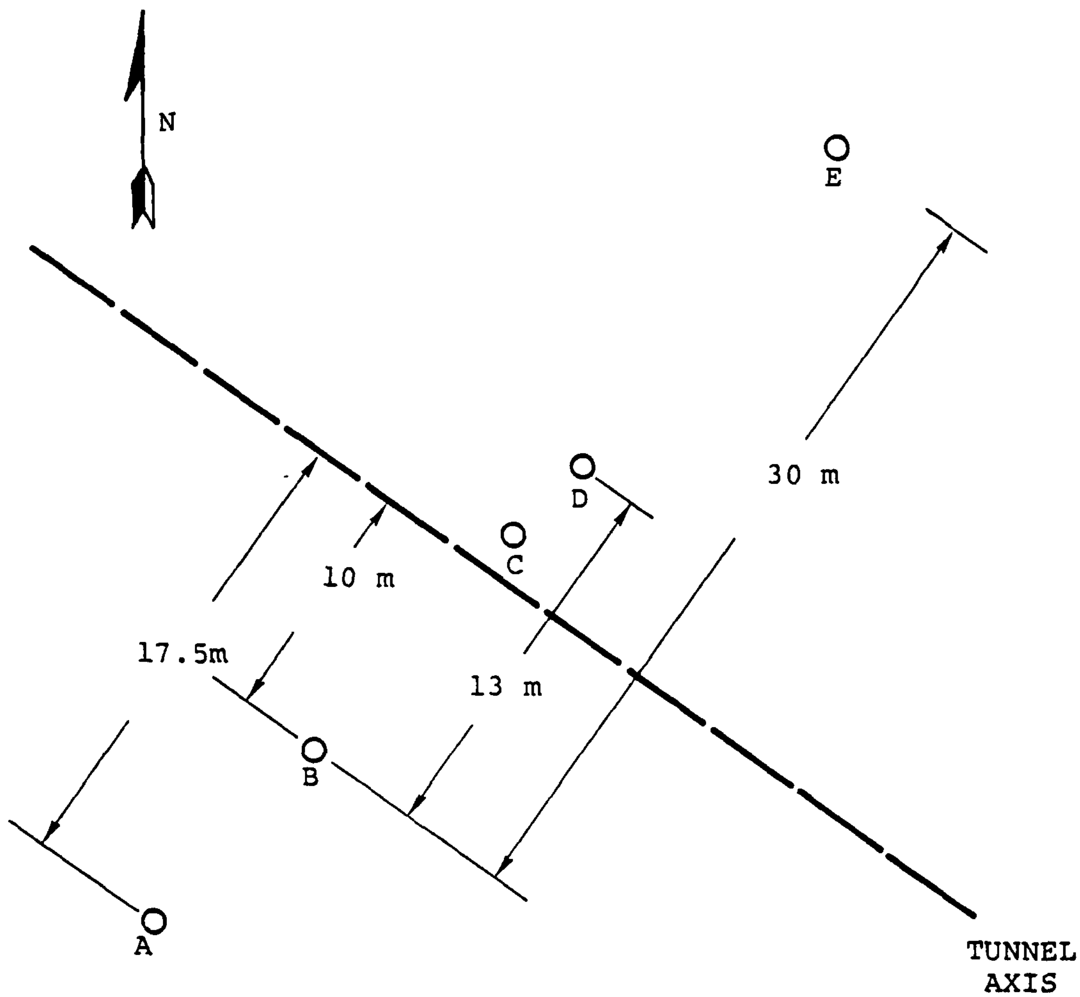


Figure 2. Location of surface holes

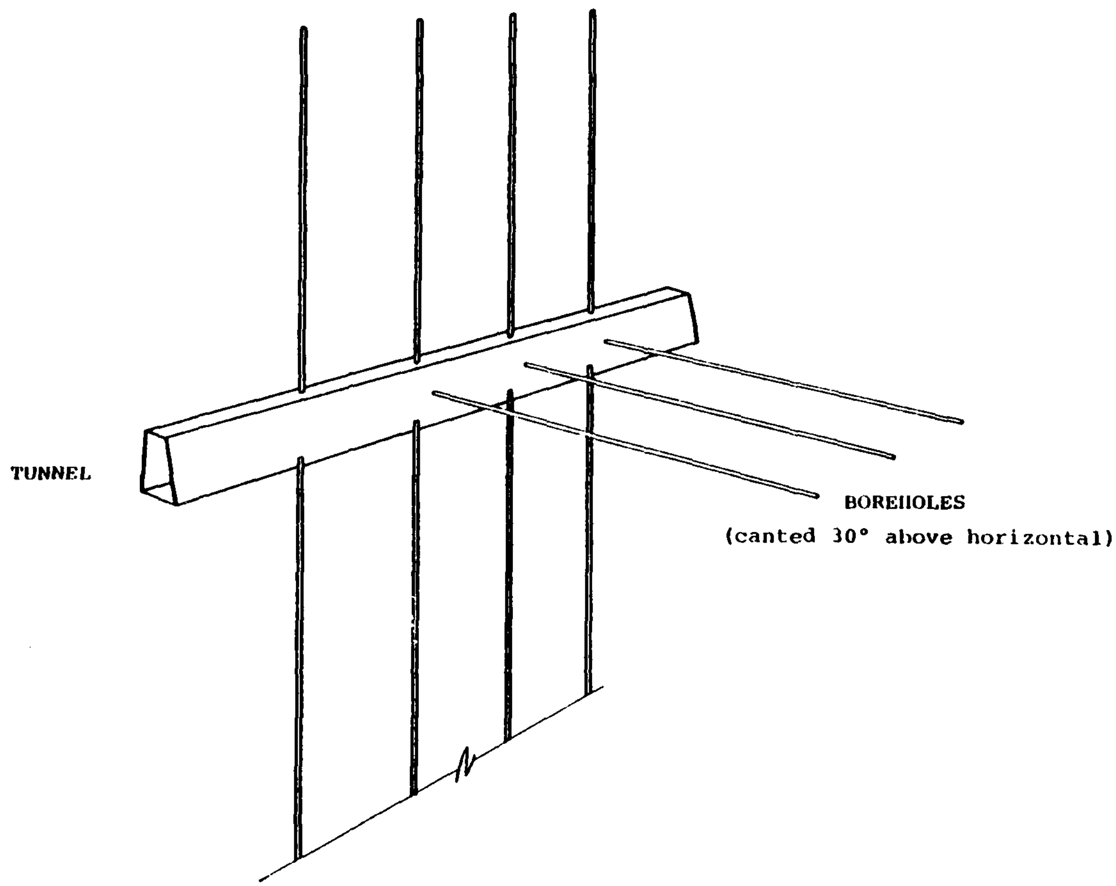


Figure 3. Underground boreholes

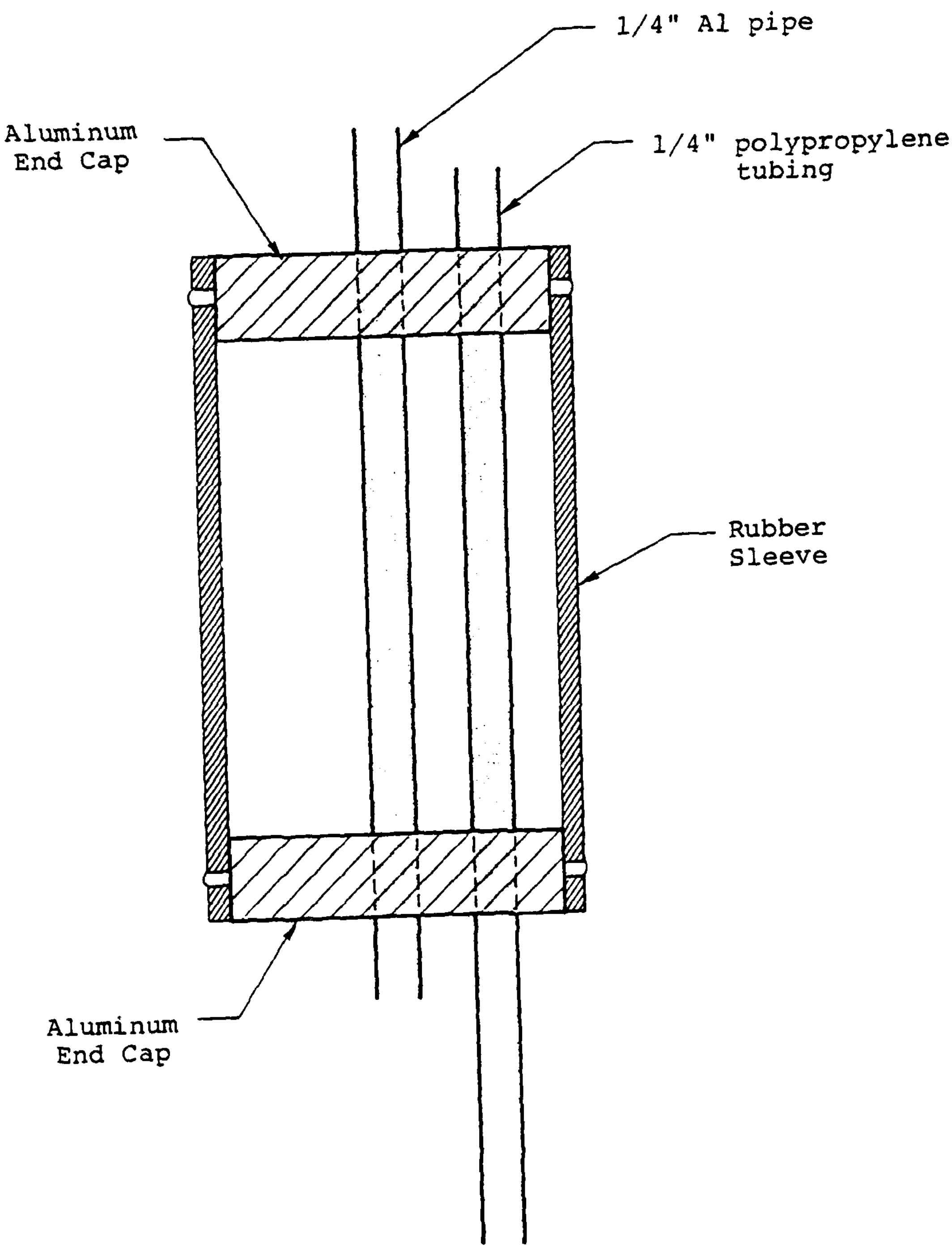


Figure 4. Downhole packer

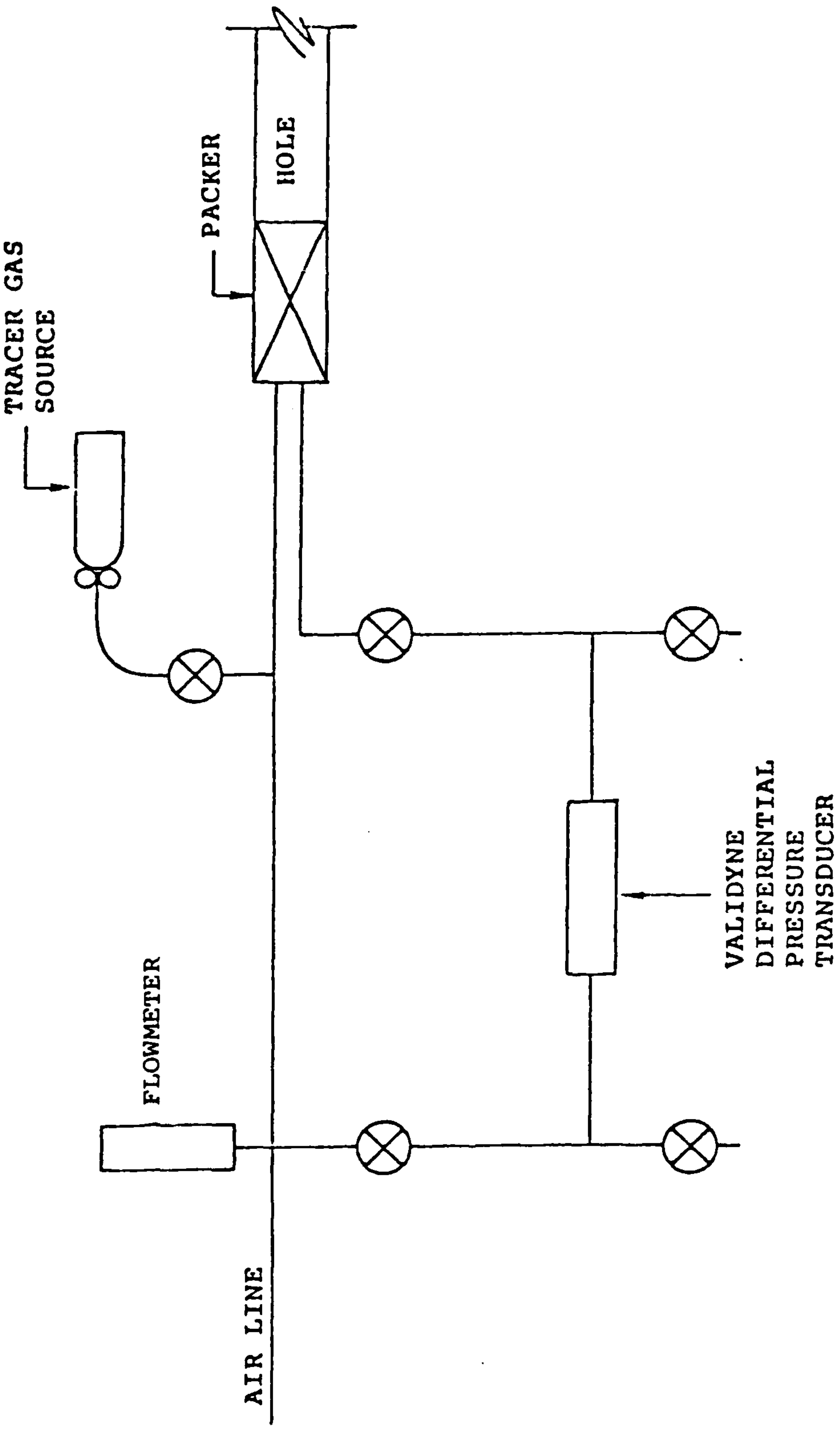


Figure 5. Sample injection manifold

In holes which showed some leakage, i.e., a nonzero flow rate under steady state conditions, a second series of compressed air flow tests was undertaken. These so-called interval tests were performed using a straddle packer with a six-meter separation as shown in Figure 6. Compressed air was injected through the one-fourth inch aluminum pipe shown. Downhole pressure was monitored through the polypropylene hose extending into the straddled zone.

An individual gas flow test was deemed to be complete when the driving pressure, the downhole pressure, and the gas flow rate remained constant for some reasonable (generally 15 to 20 minutes) period of time.

Each of these interval tests required on the order of 60 minutes to perform. This total time interval included the setting of the packers, performance of the actual test, deflation of the packers, and resetting the straddle packers at another interval.

The gas flow data are summarized in Table 1.

The zones referred to as bottom, middle, and top correspond to six meter intervals up each borehole starting with the lower packer of straddle packer system set to water level (for A and B) or to total hole depth (for D and E). Each subsequent zone is determined by moving the packer uphole six meters (18 feet).

Straddle packers were never brought closer than six meters to the surface to avoid the possibility of measuring leakage paths through poorly consolidated surface material.

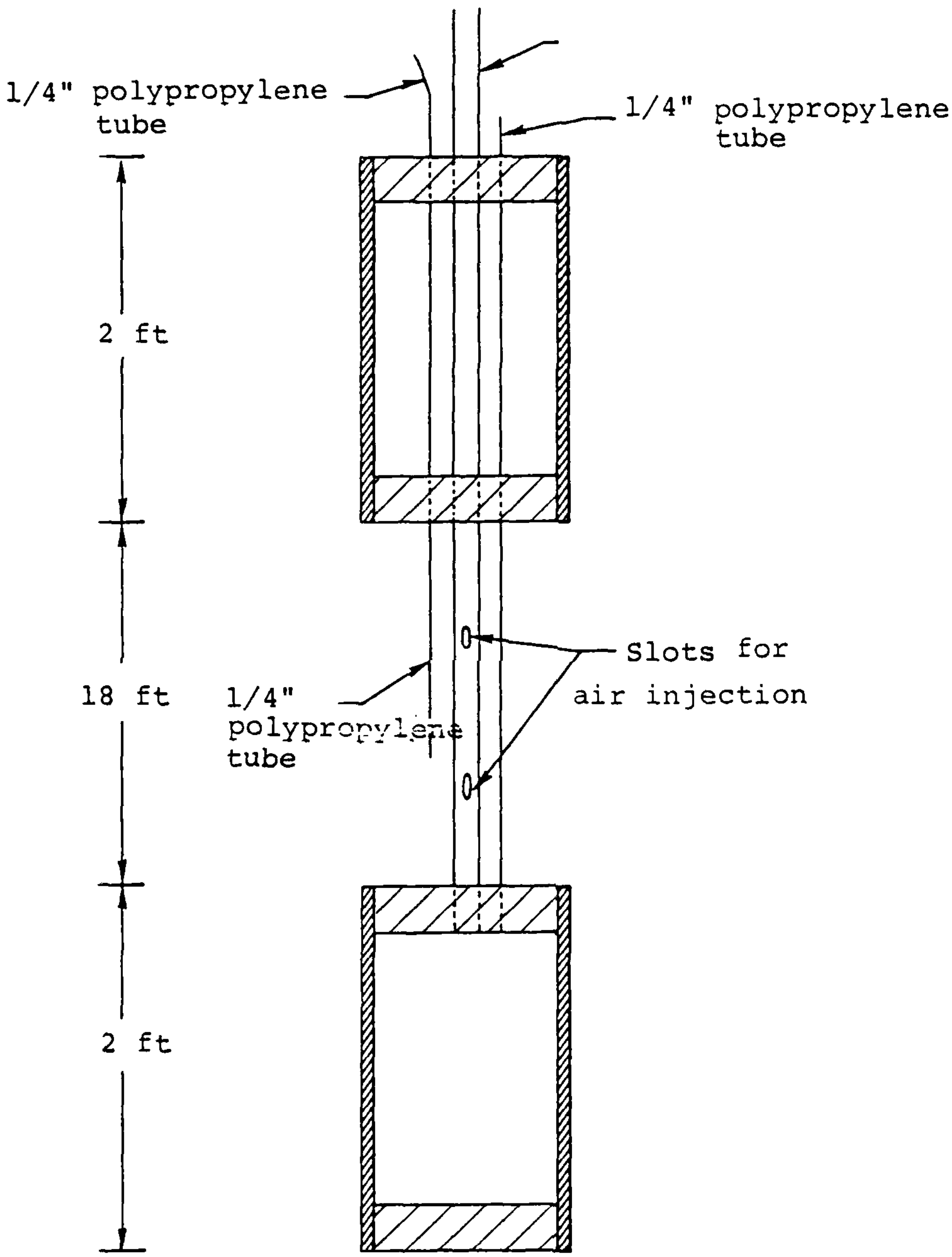


Figure 6. Straddle packer

Table 1

Initial Gas Flow Into Borehole

Hole	Zone	Flow (SCPM)	P_{drive} (psig)	$P_{downhole}$ (psig)
A	Whole hole	4.3	20.9	6.6
A	Top	1.95	15.0	8.4
A	Middle	2.06	14.2	5.9
A	Bottom	0.46	2.6	25.8
B	Whole hole	3.6	30.4	24.6
B	Top	0	24.8	24.8
B	Middle	0	29.5	29.5
B	Bottom	2.1	20.5	15.2
D	Whole hole	0	30.0	30.0
E	Whole hole	1.9	12.7	4.8

Permeability of the fractured, igneous rock was caused by existing fractures. It is possible to interpret the gas flow measurements in terms of an equivalent crack width. One can calculate this width using the relation

$$B^3 = \frac{3}{4\Pi} \frac{P_\infty}{\rho_\infty} \mu \frac{\ell n\left(\frac{r_0}{r_\infty}\right)}{\left[P_0^2 - P_\infty^2\right]} \frac{Q}{N}$$

where

B = 1/2 crack width

N = number of cracks

Q = mass flow rate

P_∞ = local atmospheric pressure

ρ_∞ = local atmospheric density

P_0 = driving pressure

r_0 = radius of borehole

r_∞ = distance to free surface (at which P_∞ is measured)

μ = viscosity of gas

Laminar flow is assumed.

In Table 2, we present crack widths for the various zones assuming N=1 in each zone.

On the basis of the data in Table 2, one zone in Borehole A and one zone in Borehole B were chosen for further study. These appeared to be the "leakiest" zones and thus, the most likely zones to communicate with a tunnel. The bottom zone of the B Borehole and the middle zone of the A Borehole, accordingly, were chosen for further study.

In order to attempt to demonstrate communication with the tunnel, these zones were repressurized with compressed air tagged with distinct tracer gas. Freon C-318 (octafluorocyclobutane C_4F_8) and Freon-12 (difluorodichloromethane CCl_2F_2) were chosen as the tracer gases. Neither of these gases possessed significant background and neither of these gases had been used in the previous year's effort. Both gases

Table 2

Crack Widths Calculated from Flow Measurements, in Straddle Packed Boreholes

Hole	Zone	Crack Width (Inches)
A	Top	0.004
A	Middle	0.006
A	Bottom	0.002
B	Bottom	0.004
E	Middle	0.006

exhibit a high electron-capture response and are easily distinguishable utilizing the techniques of electron-capture gas chromatography. Tracer gases were sensed utilizing a proprietary S-Cubed field monitoring gas chromatograph.

Monitoring for these tracer gases in the tunnel was accomplished by taking grab samples with 12cc disposable polypropylene syringes. Sampling was performed in the vicinity of the underground boreholes at approximately 15-minute intervals.

Compressed air tagged with Freon C-318 was injected into the bottom of the Borehole B hole with the pressure and flow characteristics indicated in Table 3. A definite tracer arrival was noted within the tunnel proper in approximately 100 minutes. Compressed air tagged with Freon 12 was injected into the middle zone of Borehole A with the pressure and flow characteristics also given in Table 3. A definite tracer arrival was discovered within the tunnel in approximately 110 minutes. In each case an audible hiss or whistle was heard on the south wall of the tunnel five to ten minutes prior to tracer arrival. It is interesting to note that these two tracers entered the tunnel at spatially distinct places. During the time of the experiment no Freon 12 was detected at the Freon C-318 arrival point and vice versa.

The second portion of the fielding effort examined the feasibility of injecting an inert liquid (water) into the tunnel through the fracture system discovered using compressed air and tracer gases. We tagged the water with one of two UV fluorescent dyes. One fluoresced strongly in yellow-green, the other fluoresced red when subjected to UV light. Initially, one, then later, two commercially available water heater tanks were used as reservoirs for the dye-tagged water. Injection pressure of the water was controlled by controlling gas pressure applied to the injection tank.

Table 3

Pressure, Flow and Tracer Gas Data
for Straddle Pack Communications Test

Hole	Zone	Flow	P_{drive}	$P_{downhole}$	Initial Tracer Concentration
A	Middle	4.7	25.6	11.0	10^{-5}
B	Bottom	2.7	25.8	19.4	10^{-3}

Our first experiment utilized only one water tank; however, we very rapidly used considerably more water than initial calculations had indicated might be necessary.

For the first experiment, dye-tagged water was injected into the bottom zone of Borehole B using the straddle packer used previously for interval gas injection.

Packers were set with 80 psi pressure. The driving pressure to the water tank was approximately 35 psig. With the pressurization and flow conditions indicated in Table 4, distinct yellow-green fluorescent dye was detected in Hole A in approximately 30 minutes. Continuation of the experiments for an additional 90 minutes after the detection of the dye-tagged water arrival in the A borehole showed no indication of dye-tagged water arriving within the tunnel complex. During the period of performance of this experiment, a technician was stationed within the tunnel complex in the region of anticipated arrival, scanning with a portable UV source. No fluorescence attributable to the dye-tagged water was detected.

Upon examining the vertically down boreholes in the tunnel on the morning after the initial liquid injection experiment was performed, yellow-green fluorescence was noticed in the two boreholes closest to the portal. During the previous day's liquid injection, these boreholes made copious water. Recall that these boreholes extend ten meters below the floor of the tunnel. Yellow-green fluorescent dye <u>never</u> entered the tunnel directly during our experiments.

When water levels were first measured in Holes A and B in October 1976, they were ten meters above the adit floor. The vertical holes drilled down in the mine drained these levels to the floor level. We thus already knew that the boreholes in the mine intersected fractures that provided flow paths not intersecting the adit.

Table 4

Operating Conditions During Liquid Injection

Dye Type	Borehole/ Zone	Gas Pressure (psig)	Internal Depth (ft)	Flow (GPM)
Yellow-Green	B - Bottom	35.0	65 to 83	0.45
Red	B - Bottom	37.5	65 to 83	0.48

A second experiment was performed from the same borehole utilizing red fluorescent dye-tagged water. This experiment was done with 40- and 50-gallon water tanks in parallel, allowing us to have essentially continuous supply of dye-tagged water. A sketch of this system is presented in Figure 7. The pressure and flow conditions are again shown in Table 4. In this experiment, red dye was apparent in approximately two hours and ten minutes in the A Borehole. The test was continued for an additional 150 minutes with no indication of red fluorescence within the tunnel. The lengthening of the arrival time at the A Borehole is probably due to the fact that in the initial experiment the crack (or cracks) was empty, while in the second liquid injection it was still full of water from the previous day's experiment.

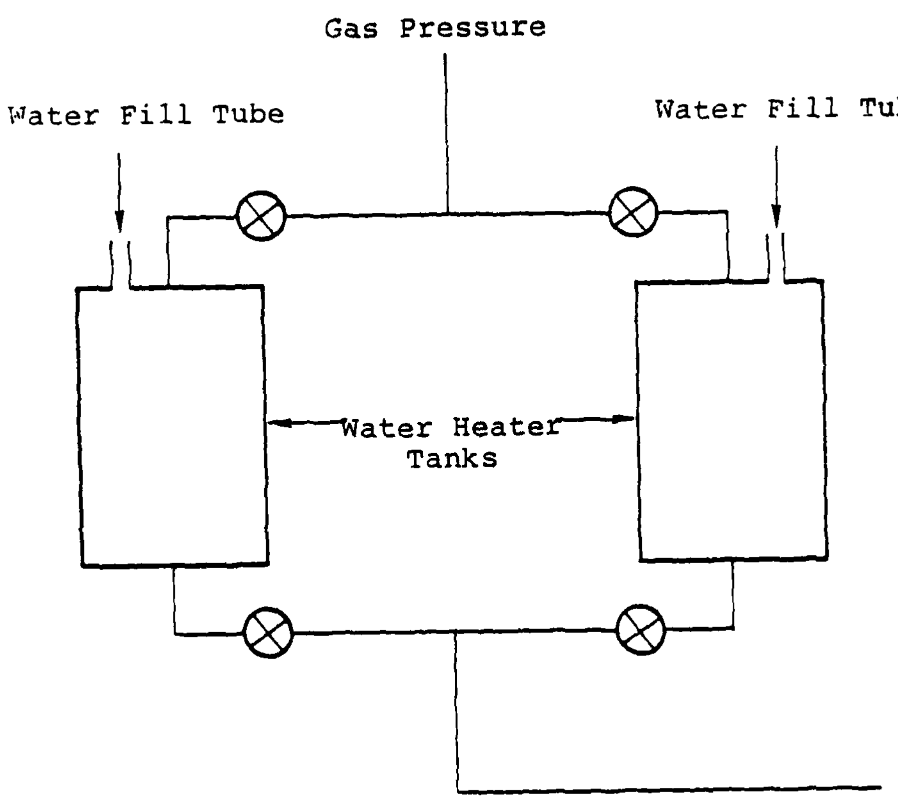


Figure 7. Water-injection system

5. GAS EXPLOSION PROPAGATION IN THIN CRACKS

Many studies of deflagration propagation and quenching in circular tubes have appeared in the literature. Some recent work has also explored deflagration quenching between closely separated flat plates. There is, however, a paucity of corresponding literature for gas-phase detonation. Detonations of acetylene/oxygen mixtures have, for example, been observed in tubes as small as 0.040-inch diameter, but there appear to be no references reporting controlled experiments to determine the gas-phase detonation quenching distance for propagation between parallel plates.

Accordingly, a series of experiments was undertaken at our Green Farm Test Site. These experiments used stoichiometric and fuel-rich mixtures of hydrogen, acetylene, and MAPP gas in oxygen.

Sketches of an experimental "thin channel" and peripheral gas handling equipment are shown in Figures 8 and 9. A photograph of the test set-up is given in Figure 10. Two one-inch by three-inch by 12-foot cold-finished 1018 steel flats were milled on facing surfaces and joined with 1/4-20 cap screws spaced every three inches. Shim stock spacers cut into one-half inch by two and one-half inch strips were placed between each pair of bolts to maintain uniform separation along the full length of the channel. A single continuous 0.275-inch diameter Viton o-ring was used as a seal. The o-ring groove was cut so as to provide 15 to 33 percent squeeze for plate separations between zero and 0.040 inch.

At one end of the channel a three-quarters inch ID by 24-inch long steel igniter tube was welded to the lower plate, perpendicular to the channel surface. A gas supply

B: Bottle valve
R: Regulator
S: Shutoff valve
C: Check Valve
FL: Flame arrestor
SOL: Servo operated ball valve
C2: 1/3 psi check valve (vent)
M: Metering valve
V: Vacuum pump
P: Premix tank
SP: Spark plug
I: Igniter
F: Fuel Tank
XDCR: Pressure transducer
TOA: Time-of-arrival gauge

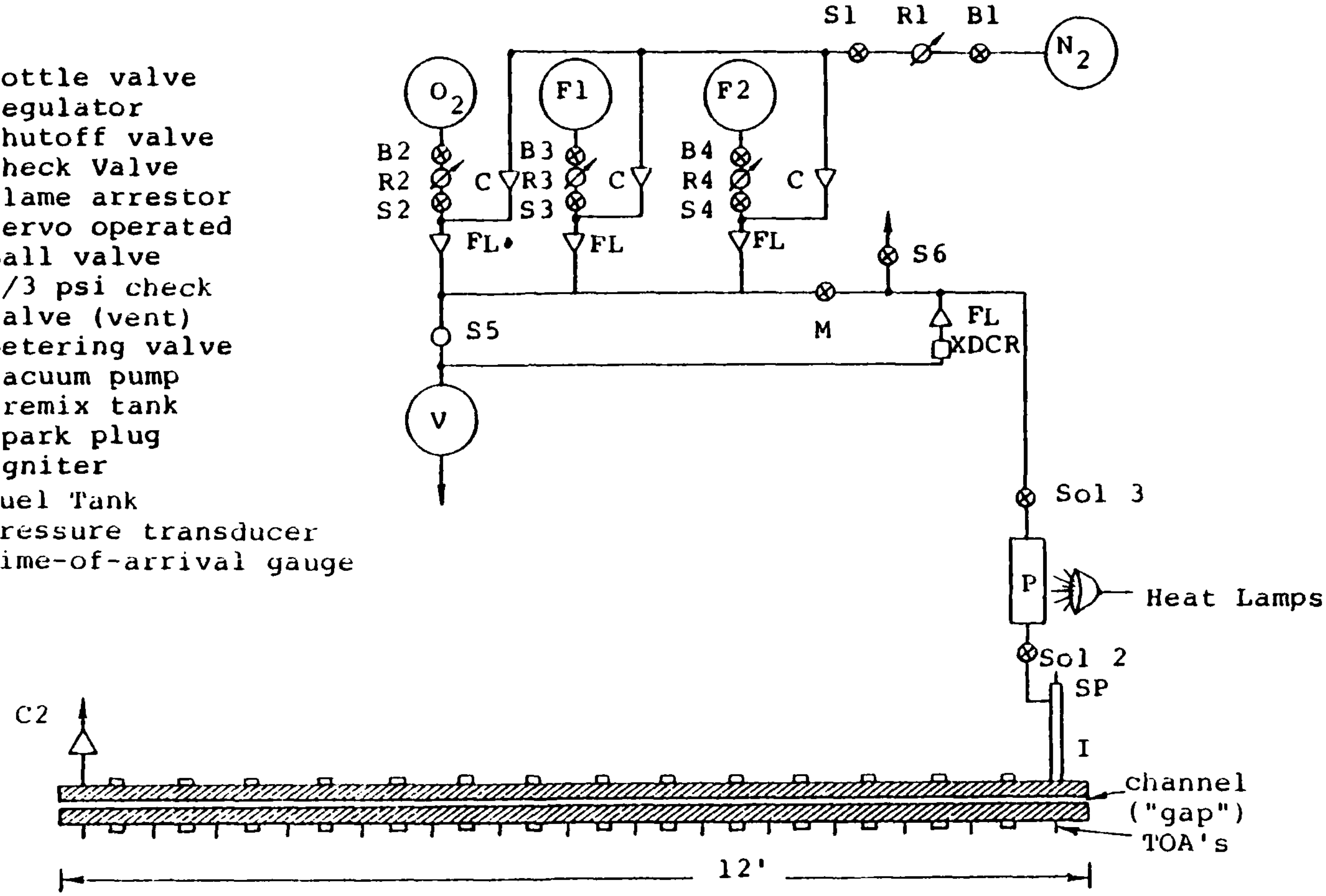


Figure 8. Schematic representation of experimental equipment

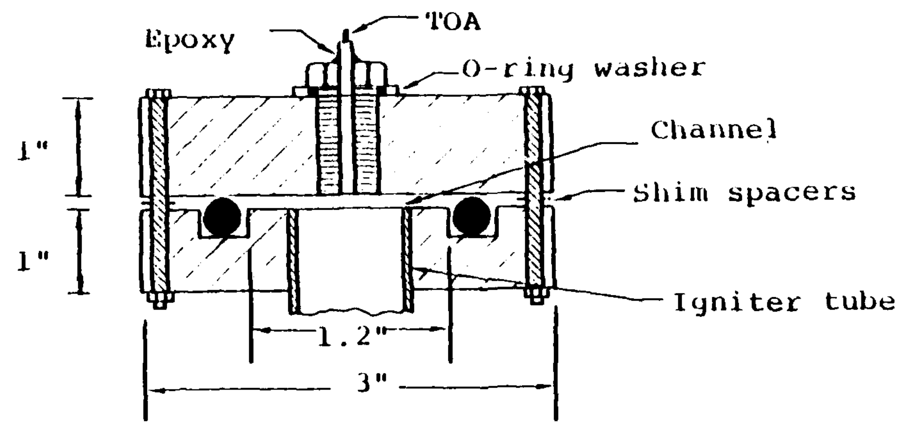
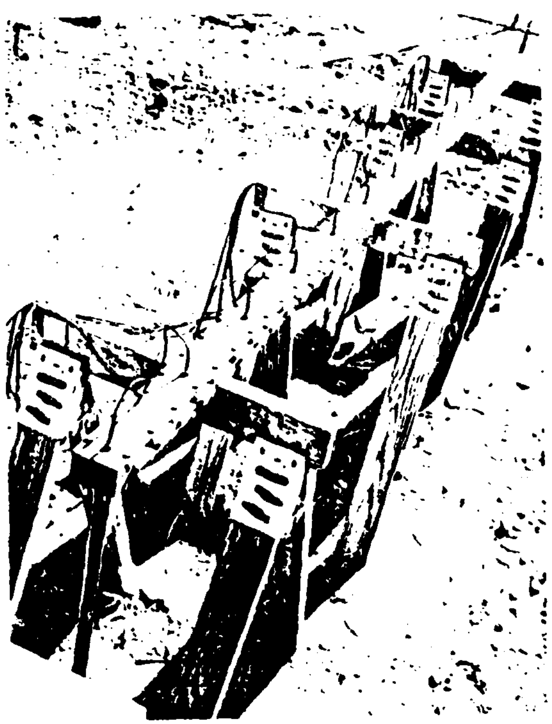
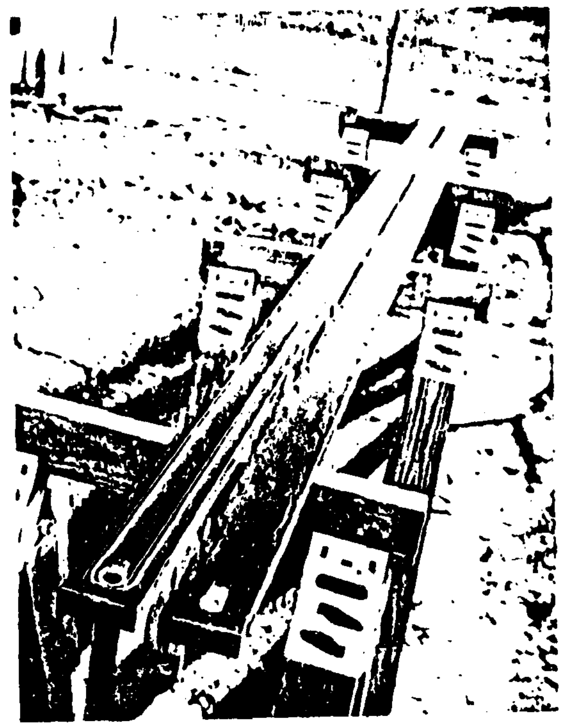


Figure 9. Cross-sectional schematic of detonation channel (not to scale)



(a)



(b)

Figure 10. Experimental detonation channel
(a) Assembled
(b) Inside Surface of Plates, Teflon-coated

inlet and spark plug mounting were provided at the lower end of this igniter. At the opposite end of the channel an inlet vent was installed and equipped with a check valve (1/3 psi cracking pressure).

Instrumentation consisted of fifteen time-of-arrival (TOA) gauges installed every 0.25 m along the channel. The gauges used were 1/8-inch OD piezoelectric pressure transducers manufactured by Dynasem, Incorporated. These were epoxied into holes drilled through the centers of 5/16-18 steel hex-head cap screws, as illustrated in Figure 9. The assemblies were then screwed into the top plate of the channel. Sealing was effected by use of washers manufactured by Parker, Incorporated, which contain integral rubber o-ring seals. The length of each TOA assembly was individually adjusted so that when installed the working face would be flush with the upper inside surface of the channel, within ±0.001 inch. The outputs from the TOA's were summed through fifteen unity gain amplifiers (used as buffers) and stored on a magnetic disk with a Nicolet digital transient recorder. A sketch of a single channel of the summer is shown in Figure 11.

Gas preparation, loading, and firing were accomplished as follows. First, both of the servo-controlled ball valves shown in Figure 8 were opened, and the channel, "premix" tank, and plumbing were evacuated. The ball valve on the channel side of the premix tank was then closed. The premix tank was next charged with oxygen and then with fuel, using the partial pressure method. At the end of this operation, the mixture pressure in the premix tank was five psig. The 0.13 ft^3 of premix was "stirred" by thermally induced convection (using heat lamps) for approximately five minutes. The channel-side ball valve was then opened, allowing the premix to fill the channel. The pressure in the premix bottle and channel equalized to about two psig. Subsequently,

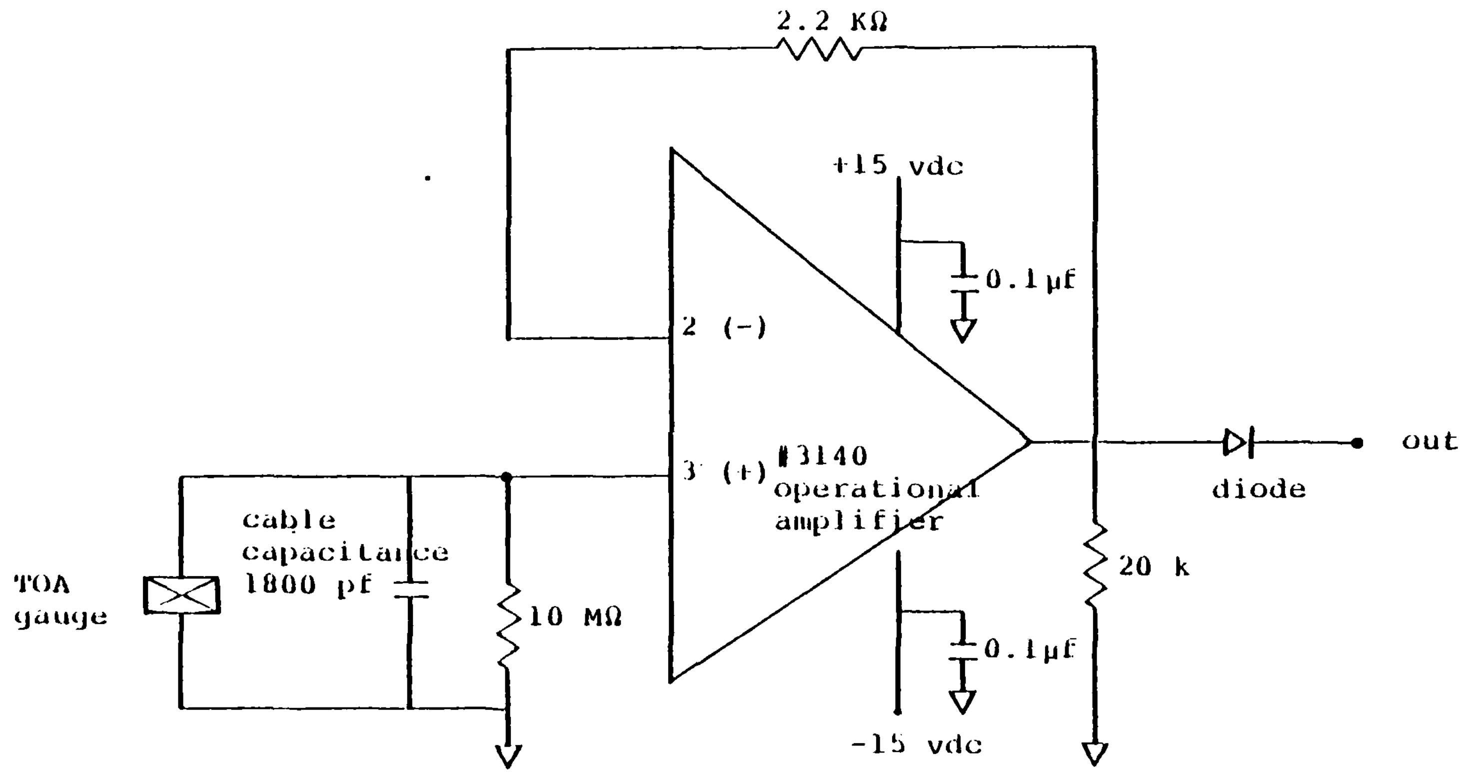


Figure 11. Single channel of unity gain summing buffer amplifier

the system would spontaneously blow down, through the vent check valve, to 1/3 psig. After isolating the channel and purging the plumbing, ignition was accomplished by firing the spark plug (which was gapped to about 0.10 inch). This would initiate a deflagration in the igniter tube that, in turn, would normally pass through transition to detonation. A strong shock wave, reinforced by reflections, would then enter the channel when this initiating detonation reached the top plate.

The gas mixtures tested in these experiments are summarized in Table 5. The "rich mixtures" had mole fractions of fuel ten percent above stoichiometric. Plate separations ("gaps") between 0.001 inch and 0.040 inch were tested.

After each run, the digitally stored data from the summer output and from individual TOA gauges were displayed on an oscilloscope (built into the transient recorder). Two of the best examples of these displays are reproduced in Figure 12.* Zero time was defined for each run as the moment when the detonation in the initiator tube reached the channel. The first TOA gauge was located on the initiator centerline and the pulse from this gauge was used to trigger the transient recorder. The time from t = 0 to the leading edge of each successive "spike" was then carefully measured and the resulting wave-position versus time-of-arrival was plotted. A typical plot of this type is given in Figure 13, which is an example of a run in which the detonation successfully propagated through the entire length of the channel. An example of marginal detonation propagation is shown in Figure 14. For those cases in which detonation failed, it usually did so within one meter from the igniter. Four examples of summer records for runs with detonation failures are given in the upper traces of Figure 15.

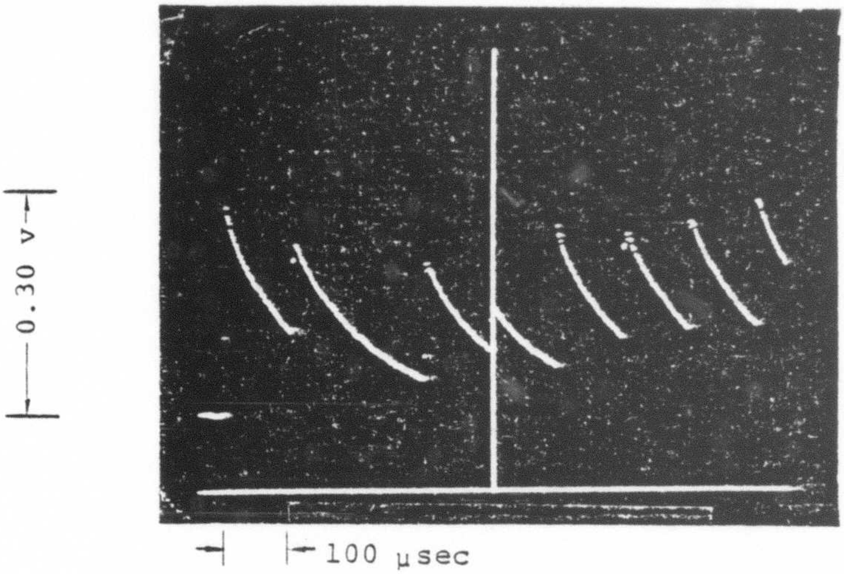
* It should be noted that the TOA gauges are not calibrated and their gain is variable between units.

Table 5

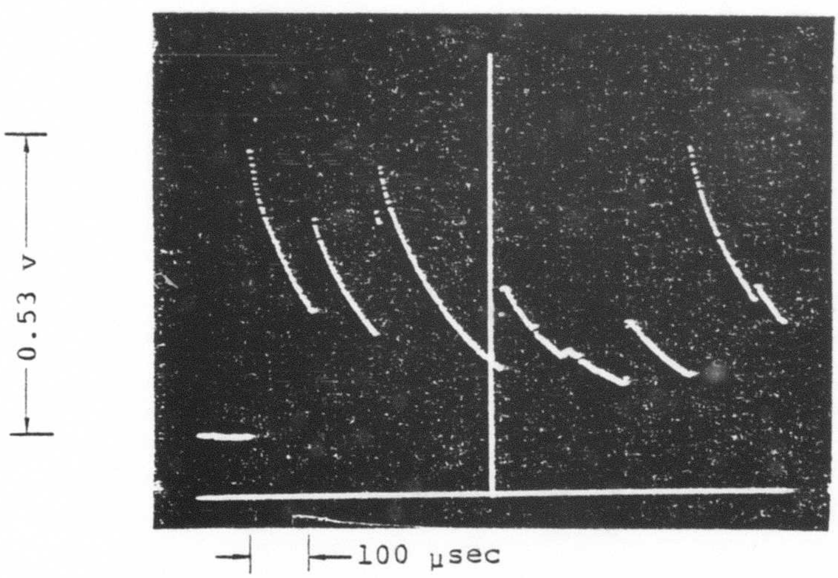
Gas Mixtures Tested

FUEL	MOLE FRACTIONS STOICHIOMETRIC	RICH
Acetylene, C_2H_2	C_2H_2 - 0.286 O_2 - 0.714	0.31 0.69
Hydrogen, H_2	H_2 - 0.67 O_2 - 0.33	0.74 0.26
Carbon Monoxide, CO	CO - 0.67 O_2 - 0.33	0.74 0.26
Carbon Monoxide/ Hydrogen, CO + H_2	CO - 0.62 H_2 - 0.05 O_2 - 0.33	0.68 0.06 0.27
MAPP Gas*	MAPP - 0.190 O_2 - 0.810	0.21 0.79

*MAPP gas is a mixture of methyl acetylene (51% by volume), propane (26%) and propadiene (23%).



(a)



(b)

Figure 12. Summer Output from TOA Probes #2-8 and 5-10, (#4 inoperative), counted from igniter end of channel. Perpendicular lines are reference cursors. Mixture is stoichiometric C_2H_2/O_2; (a) 0.010-inch gas, (b) 0.005-inch gap. Successful detonation, both cases; Teflon-coated steel plates.

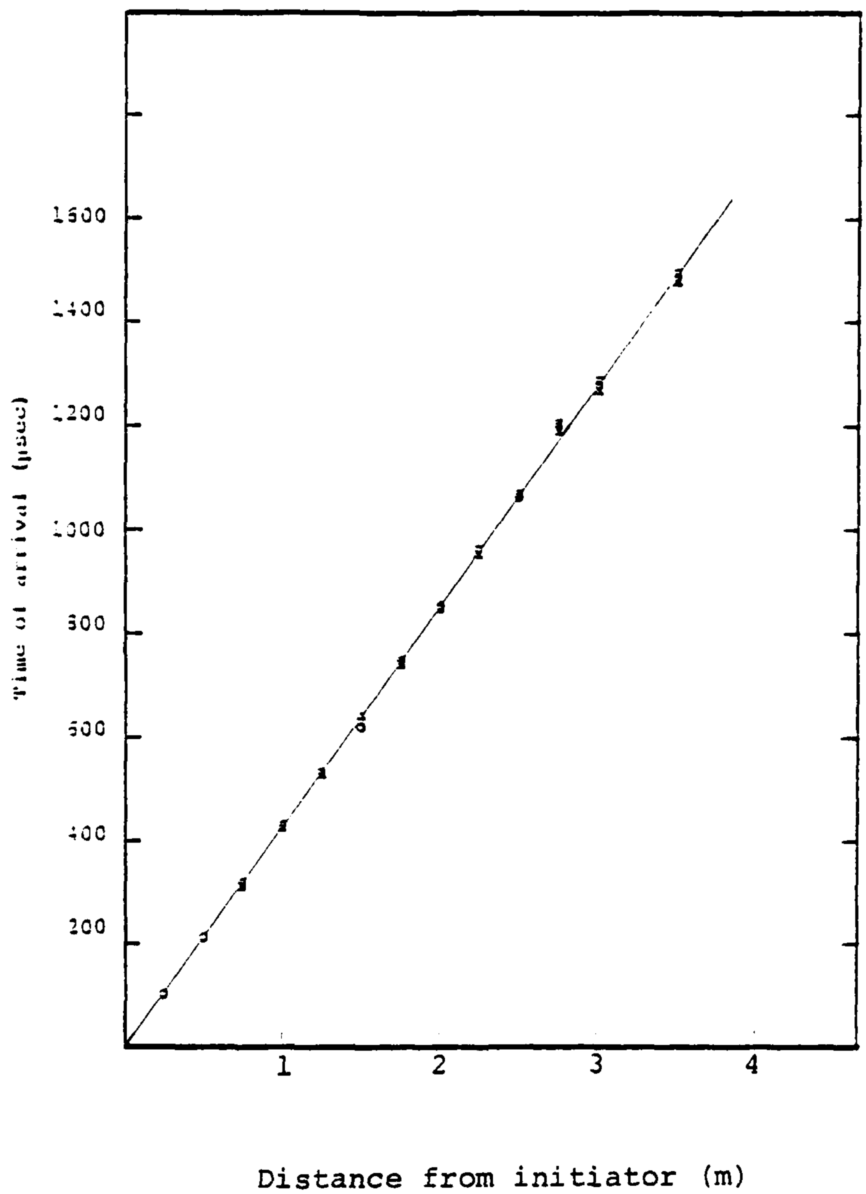


Figure 13. Time of arrival versus gauge position for Stoichiometric C_2H_2/O_2 mixture; 0.040-inch gap, three tests. Successful detonation propagation; 2350 m/sec average wave velocity.

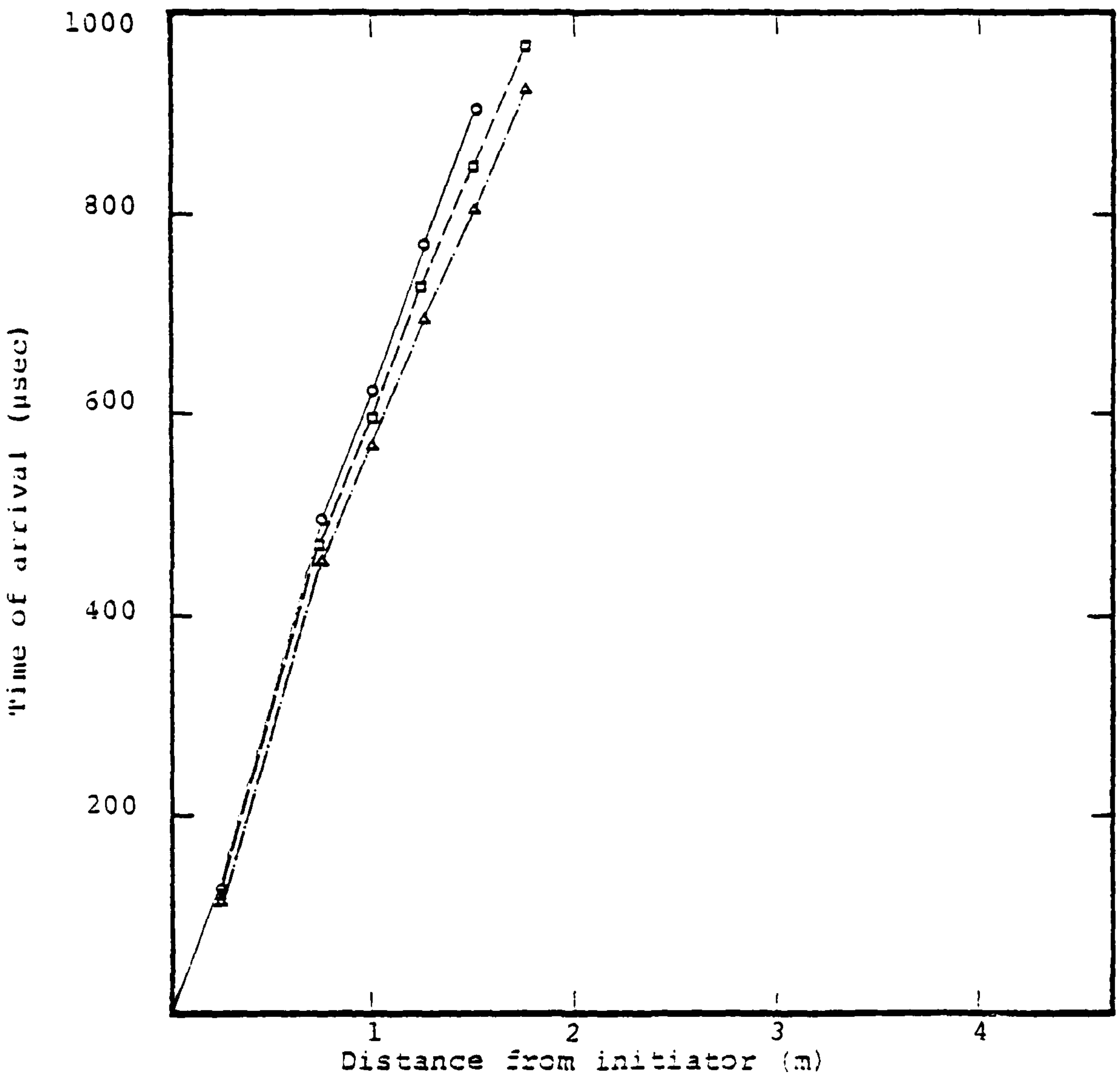
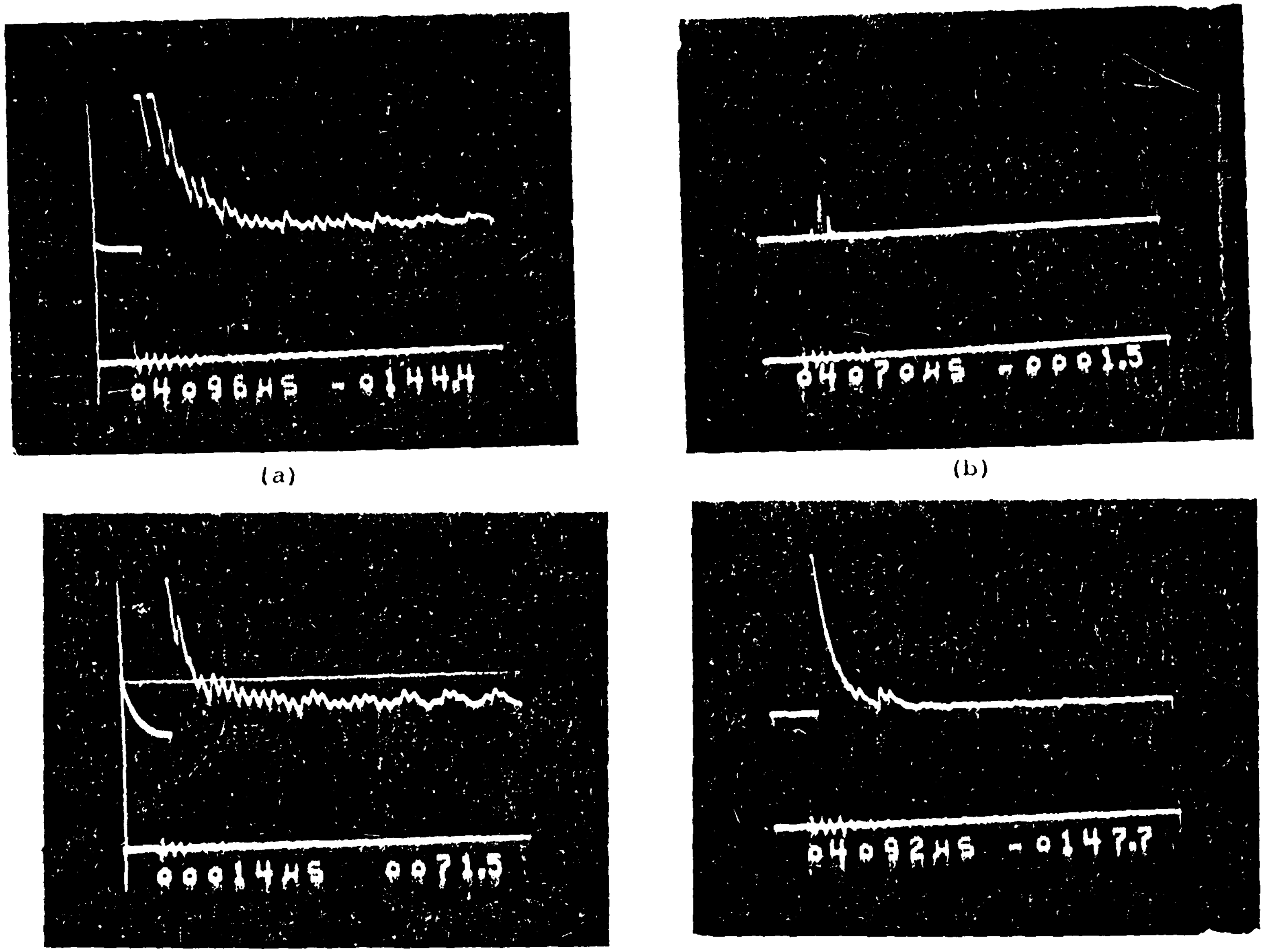


Figure 14. Time of arrival versus gauge position for Stoichiometric MAPP/O mixture, 0.010-inch gap, three tests. Marginal detonation propagation.



(a) (b)

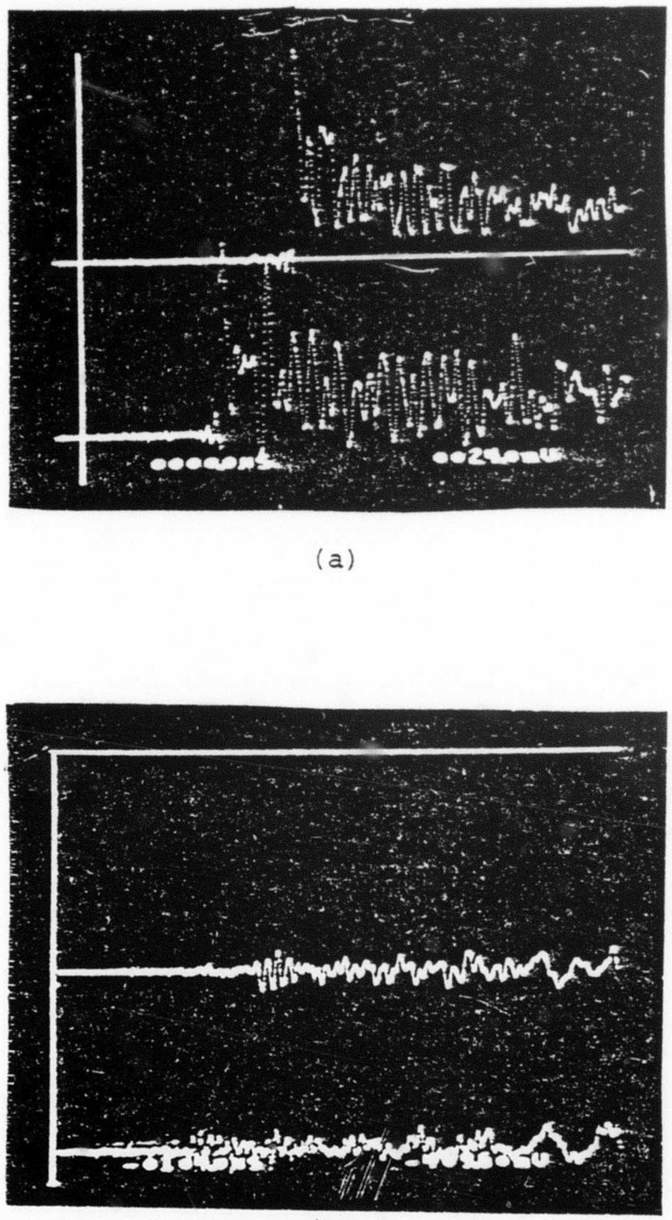
(c) (d)

Figure 15. Summer output from TOA probes #3-15 (upper traces) and probe #2 (lower traces). Detonation failure in all cases at 0.020-inch gap, plain steel. (a) stoich MAPP/O_2, (b) rich MAPP/O_2, (c) rich C_2H_2/O_2, (d) stoich H_2/O_2.

Detonation was judged to have been successful if the velocity was reasonably constant and if this velocity was close to that known to obtain in "large" diameter tubes. (This was the case, for example, for the run shown in Figure 13.) At least three runs were made with each fuel/oxygen mixture at each plate separation to assure repeatability, both for successful and for unsuccessful detonations. A clear distinction between detonation success and failure could also usually be observed from the pressure records of individual TOA transducers. This difference is illustrated by the two runs shown in Figure 16.

Although the particular TOA gauges used in this experiment exhibited considerable ringing, the leading edges of the traces were usually quite clearly defined. When the front of a detonation traversed these gauges, their amplitude increased significantly, with risetimes below 2 μs. Characteristic examples are shown in Figure 17.

To distinguish between the TOA records resulting from detonations and those obtained from simple stress waves propagating through the plates, several tests were conducted in which impulses of various kinds were applied to the plates. The single-gauge records from four of these tests are given in Figure 18. These should be compared with Figures 16 and 17. In one test, the plates were struck with a mallet near the initiator on its bottom and end sides (Figures 18a and 18b). In another test, a one-inch diameter rubber o-ring was compressed between the two plates at the initiator opening, to isolate the initiator from the rest of the channel. The initiator was loaded and fired using acetylene/oxygen in order to reproduce the impact of the initiator detonation as it reflects of the top plate, without the possibility of detonation occuring in the channel (Figure 18). In still another test, an explosives detonator was fastened to a one-half inch wood block that in turn was taped securely to the



(a)

(b)

Figure 16. Output from TOA gauges #15 (upper traces) and #10 (lower traces). For stoichiometric MAPP/O_2 mixtures, plain steel plates. (a) 0.040-inch gap, successful detonation; (b) 0.020-inch gap, detonation failure.

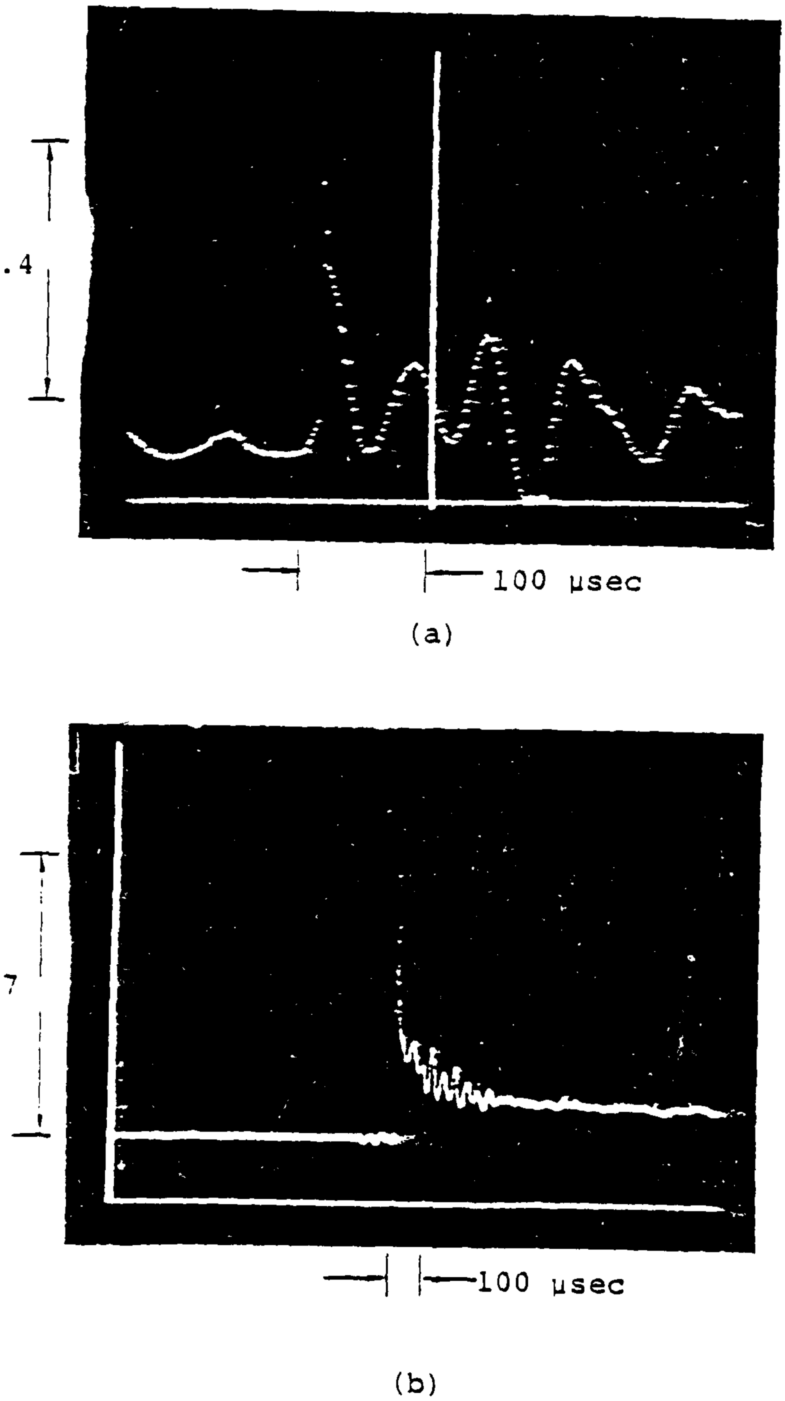
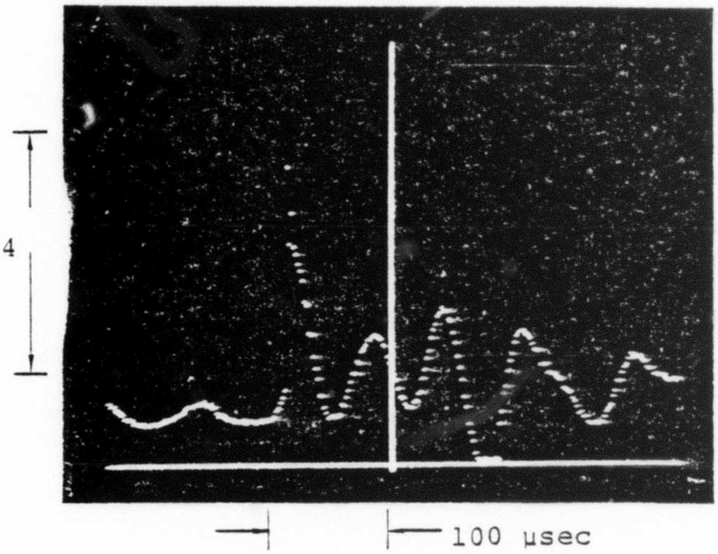
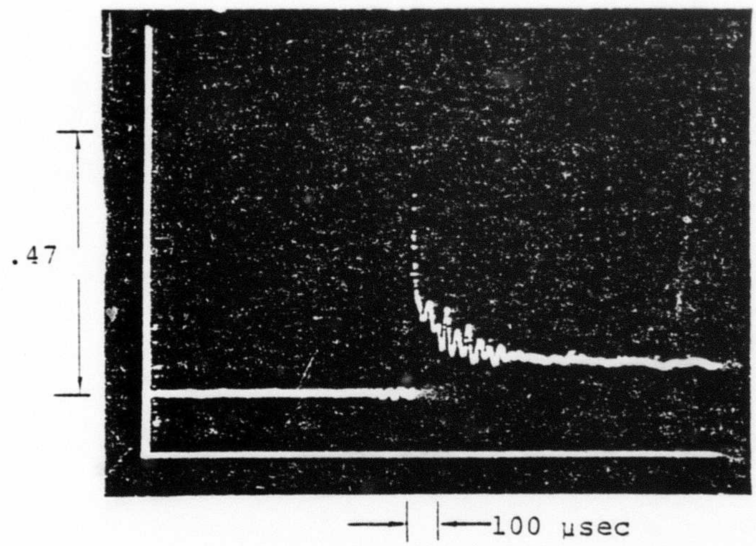


Figure 17. Output from TOA gauge #14 for stoichiometric C_2H_2/O_2 mixtures, Teflon-coated steel plates and O-ring groove fillers; (a) 0.005-inch gap; (b) 0.010-inch gap.



(a)



(b)

Figure 17. Output from TOA gauge #14 for stoichiometric C_2H_2/O_2 mixtures, Teflon-coated steel plates and O-ring groove fillers; (a) 0.005-inch gap; (b) 0.010-inch gap.

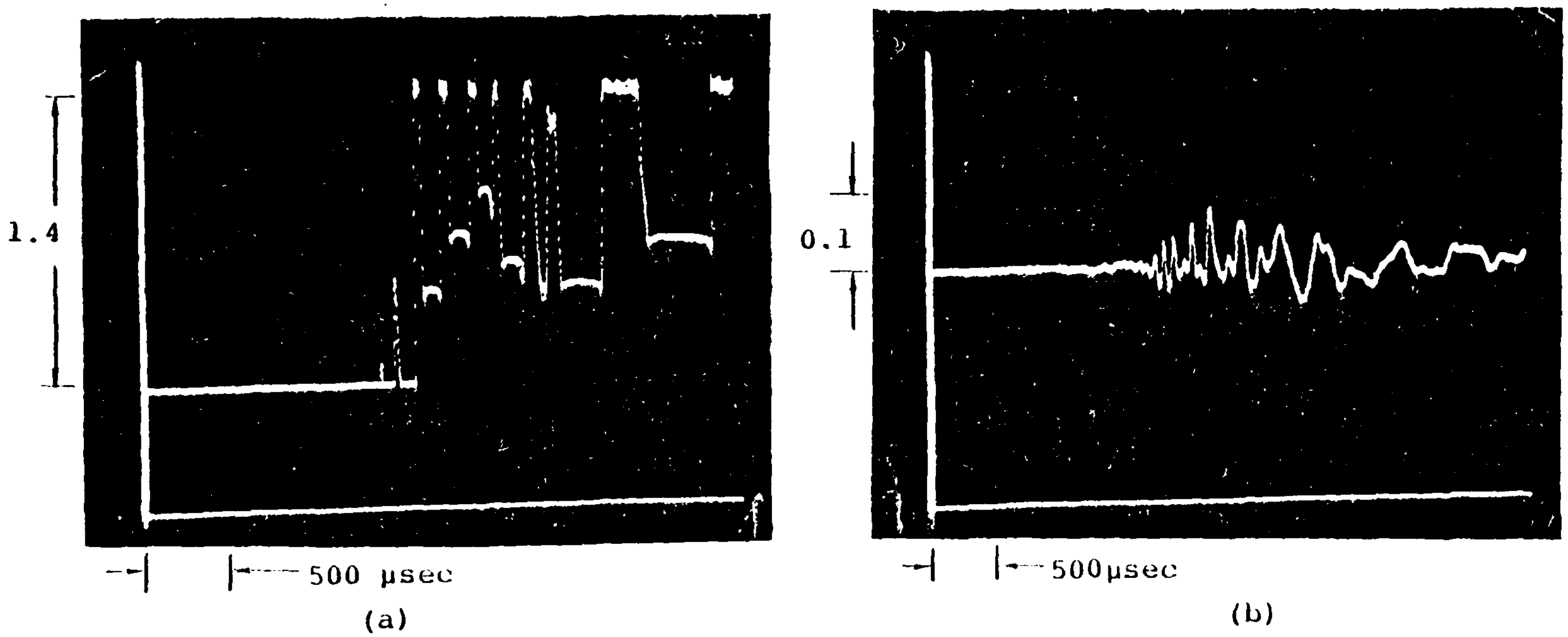
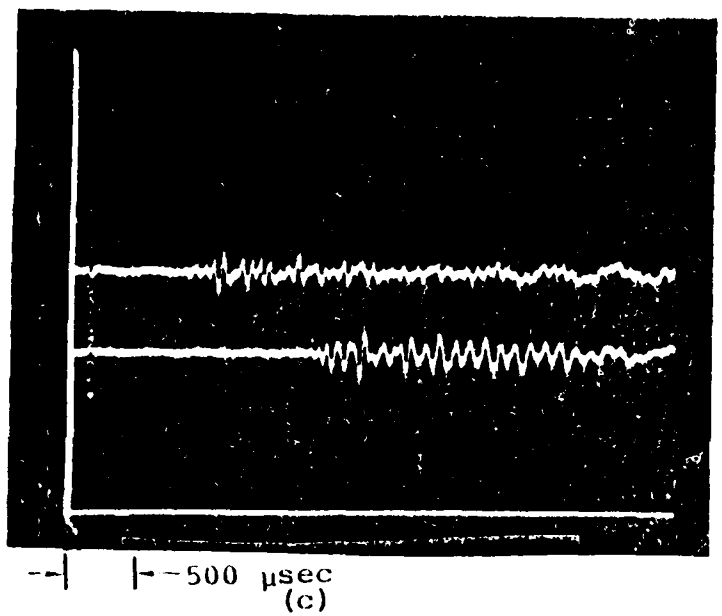


Figure 18. Characteristics of impact induced stress waves in experimental channel.
(a) Longitudinal mallet impact at igniter position, output from TOA probe #14, disassembled top plate only, wave speed ∿2560 m/sec.
(b) Transverse mallet impact at igniter location, output from TOA probe #14 assembled plates with 0.010" gap, wave speed ∿3850 m/sec.



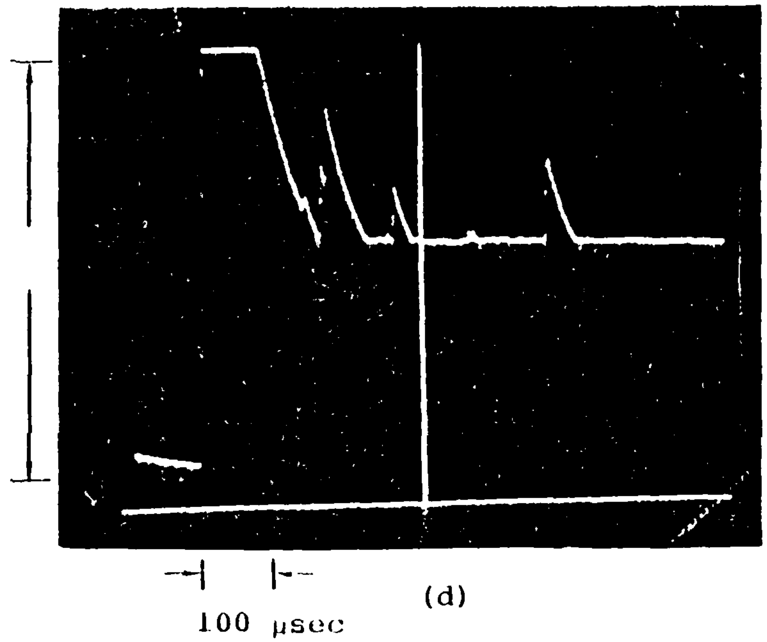


Figure 18. (cont) (c) Initiator induced transverse impact. Top trace is summer output, TOA probes #2-15, lower trace probe #1, o-ring isolation between igniter and channel gap, 0.010" gap, wave velocity ∿3050 m/sec.
(d) Detonator induced longitudinal impact from igniter end, 0.005" gap, wave velocity ∿4120 m/sec.

plates at the initiator end and fired (Figure 18). Although considerable output was obtained from all of these stimuli, none produced a TOA output that was qualitatively similar to that obtained from what was judged to be a detonation. In those stress wave tests for which a wave speed was measurable, the value was much higher than any of the observed detonation velocities.

The experimental results are summarized in Tables 6-8. Detonations were easily and repeatably produced in stoichiometric hydrogen, acetylene, and MAPP mixtures with oxygen at a plate separation of 0.040 inch (about 1 mm). Marginal detonation was observed in H_2/O_2 at a gap of 0.030 inch (the other two fuels were not tested at this gap). However, all three of these fuels, in both stoichiometric and fuel-rich proportions with oxygen, failed to detonate through a 0.020-inch gap.

Either or both of two phenomena could account for this failure; namely, (1) thermal losses to the walls of the channel owing to the increased surface-to-volume ratio in smaller gaps, and (2) chain breaking reactions at the wall surfaces which neutralize active radicals. The second of these could be of importance because of the very short diffusion times required for active species to reach the walls. It was felt that neither of these influences would be of comparable significance in cracks in rock. For that reason, it was believed that a more realistic simulation of detonation propagation through rock cracks would be achieved by coating the steel plates with Teflon. A one-mil coating of Teflon-S was accordingly applied to the inside surfaces of both steel plates, and all subsequent experiments were conducted using the coated plates.

The Teflon plating did not decrease the detonation quenching distance for H_2/O_2 mixtures below 0.030 inch.

Table 6

Summary of Acetylene/Oxygen Tests

(Normally reported stoichiometric detonation velocity in large diameter tubes is ∿2400 m/sec.)

GAP (in.)	MIXTURE	DETONATION YES	DETONATION NO	VELOCITY (m/sec)	TEFLON COATING YES	TEFLON COATING NO	O-RING PACKING YES	O-RING PACKING NO	COMMENTS
0.040	STOICH	▲		2350		▽		▽	
0.030									NOT TESTED
0.020	STOICH		▽			▽		▽	
0.020	RICH.		▽			▽		▽	
0.020	STOICH	▲		2260	▲			▽	
0.010	STOICH	▲		2240	▲			▽	
0.010	STOICH	▲		2200	▲		▲		(1)
0.008	RICH.	▲		2270	▲			▽	
0.006	STOICH	▲		2144	▲			▽	
0.005	STOICH	▲		2100	▲			▽	
0.005	STOICH			2245	▲		▲		(2)
0.003	STOICH	(4)			▲		▲		
0.001	STOICH	(4)			▲		▲		(3)

Comments: (1) 10 mil electrical tape was used; (2) 7 mil electrical tape was used; (3) no shims separating plates; (4) possible detonation.

Table 7

Summary of MAPP/Oxygen Tests

GAP (in.)	MIXTURE	DETONATION YES	DETONATION NO	VELOCITY (m/sec)	TEFLON COATING YES	TEFLON COATING NO	O-RING PACKING YES	O-RING PACKING NO	COMMENTS
0.040	STOICH	▲		2280		▽		▽	
0.030									NOT TESTED
0.020	STOICH		▽			▽		▽	
0.020	RICH		▽			▽		▽	
0.020	STOICH	▲		2160	▲			▽	
0.010	STOICH		▽		▲			▽	
0.010	RICH		▽		▲			▽	
0.008									NOT TESTED
0.006									NOT TESTED
0.005									NOT TESTED
0.003									NOT TESTED
0.001									NOT TESTED

Table 8

Summary of Hydrogen/Oxygen Tests

(Normally reported stoichiometric detonation velocity in large diameter tubes is ∿2830 m/sec.)

GAP (in.)	MIXTURE	DETONATION YES	DETONATION NO	VELOCITY (m/sec)	TEFLON COATING YES	TEFLON COATING NO	O-RING PACKING YES	O-RING PACKING NO	COMMENTS
0.040	STOICH	▲		2600		▽		▽	
0.030	STOICH	▲		2889		▽		▽	(1)
0.020	STOICH		▽			▽		▽	
0.020	RICH		▽			▽		▽	
0.020	STOICH		▽					▽	
0.020	RICH		▽		▲			▽	
0.010	STOICH		▽		▲			▽	
0.010	RICH		▽		▲			▽	
0.010	STOICH		▽		▲			▽	(2)
0.010	RICH		▽		▲			▽	(2)
0.008									NOT TESTED
0.005									NOT TESTED
0.003									NOT TESTED
0.001									NOT TESTED

Comments: (1) marginal detonation with non-consistant velocity; (2) carbon monoxide hydrogen mixture.

Carbon monoxide/oxygen mixtures were tested only at a gap of 0.020 inch and the detonation failed to propagate through the channel. Detonations in C_2H_2/O_2 were now successfully propagated through cracks as small as 0.005 inch, the smallest gap that could be set accurately.

Depth gauge measurements, taken through the TOA mounting ports, were able to establish gap uniformity to within $\pm$0.001 inch. Thus, although C_2H_2/O_2 detonations were observed when 0.003-inch and even when 0.001-inch shim spacers were installed between the plates, it is not possible to report with confidence that the gap along the centerline of the channel was of these same dimensions.

The results in C_2H_2/O_2 mixtures were quite unanticipated. This led to re-examination of the experimental hardware and in particular, to the o-ring groove which, it was felt, might possibly have presented an alternate path for the detonation. As illustrated schematically in Figure 19, a metal spacer and nonhardening putty were therefore used to fully pack the o-ring groove, and plastic tape was bridged between the top of the o-ring and the lower channel surface. (The o-ring itself, when fully compressed, filled about 90 percent of the groove volume before the additional packing.) Following these preparations, the top plate was bolted in place, then removed to examine the integrity of the packing. The inside surfaces of the plates were also cleaned before the final assembly. When reassembled, the gap was again checked with a depth gauge. Several C_2H_2/O_2 runs were repeated by these procedures with gaps of 0.010 inch and 0.005 inch. Detonations were observed in all of these tests.

In summary, detonations in H_2/O_2, C_2H_2/O_2, and MAPP/O_2 mixtures can be propagated between flat, parallel steel plates. The minimum plate separation was found to be between 0.020 inch

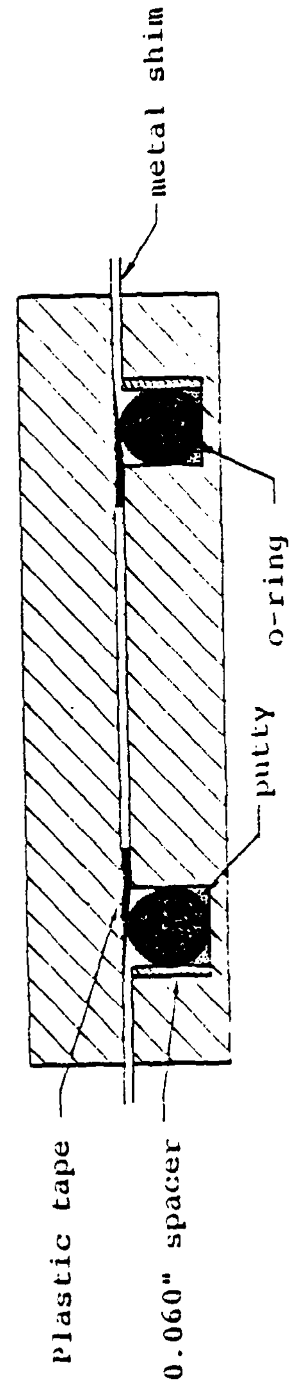


Figure 19. Schematic of channel cross-section illustrating fillers used to pack the O-ring groove.

and 0.030 inch for H_2/O_2, and between 0.020 inch and 0.040 inch for C_2H_2/O_2 and for MAPP/O_2. Detonations in these gas mixtures can also be propagated between flat, parallel steel plates coated with a 1-mil thickness of Teflon-S. In this case, the minimum plate separation is above 0.020 inch for H_2/O_2, between 0.010 inch and 0.020 inch for MAPP/O_2, and below 0.005 inch for C_2H_2/O_2. Insufficient tests with CO/O_2 were performed for similar conclusions to be drawn. Increasing fuel mole fractions to 110 percent of stoichiometric proportions did not affect these results. It is believed that detonation propagation through these gas mixtures in granite cracks is probable if the cracks are at least as wide as the detonation quenching distances corresponding to the experiments with Teflon-coated steel plates.

6. RECOMMENDATIONS

The results of S^3 tunnel work to date indicate that subsurface fluid flow measurements provide a promising validation technique for tunnel location. When existing tunnels are deep enough so that surface geophysical methods fail and cross-borehole techniques must be used, flow measurements should certainly be tried. Further work is needed, however, before we can regard the flow measurements as an operational tunnel-finding technique.

We demonstrated that acetylene-oxygen mixtures would detonate in cracks as thin as 0.005 inches. This work should be extended to measurements in cracks in real rocks, including the effects of wall roughness and water included in the cracks. Higher gas pressures should also be investigated, since they may lead to detonation in even thinner cracks. The high pressures would be useful in attaining higher rates of gas injection into a tunnel.

Many operations problems remain to be solved. In field operations, a fuel such as ethylene oxide or propylene oxide would be injected at first to form a fuel-air mixture in any nearby tunnel. High pressure would be used to reduce the time of injection and to produce turbulent mixing of fuel and air in the tunnel. The fuel would be followed by acetylene, mixed with air or oxygen, to transmit a detonation to the tunnel. Then, with no tunnel, the only explosion would be in a small amount of acetylene in cracks. With a tunnel, a large FAE mixture would detonate in the tunnel. Work is needed on the mixing process, fuel handling, and on acetylene use. Acetylene cannot be used at pressures over about 40 psi without risking spontaneous ignition.

Field work on the gas and liquid flow measurements should be extended to other sites including the various geologies that may be of interest in tunnel location. For example, quite different results might be obtained in locations having layers with inter-granular permeability rather than crack permeability. For the various geologies, we should investigate how far away boreholes can be located from a tunnel while still maintaining satisfactory flow communication.

The highest priority should be assigned to performing a complete field test in which explosive mixtures are injected into a tunnel and detonated. Seismic location of the blast should be included.

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